P. 3.1 FACTORS INFLUENCING TREEFALL RISK IN TORNADOES IN NATURAL FORESTS

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1. INTRODUCTION

While a majority of the effects used to assign F-scale ratings to tornado intensity are based upon damage to buildings and other structures (e.g. Marshall, 2003, Schaefer and Livingston, 2003), some of the criteria are based on tree damage (Fujita 1971). The importance of tree-damage characteristics becomes especially important in locations where no buildings or other structures are present to use for F-scale ratings. However, examination of patterns of tornado damage to trees in natural forests suggests that the existing tree damage metrics are overly simplistic, and that their application is likely to be vague, and perhaps even misleading.

A first difficulty with the F-scale criteria lies in the potential for alternative interpretations. For example, a criterion for F-3 damage is that "most trees in forest are uprooted". One interpretation of this statement is that most of the trees present in an affected area are uprooted, with the focus on what proportion of all trees suffer this type of windthrow. Alternatively, this statement could be interpreted to mean that among the trees that are damaged (regardless of what proportion of the total this is), most are uprooted. This is an issue of wording and thus beyond the scope of this paper; however it is notable that this author has observed tornado damage classified as F-3 and F-4 in which most trees in an area were extensively damaged, but almost exclusively by being broken in the trunk – none were uprooted.

A second difficulty arises because a number of characteristics of trees and their surroundings, as well as characteristics of the wind, combine to cause the observed patterns of tree d[1]amage (Schaetzl et al. 1989, Foster and Boose 1992, Everham and Brokaw 1996), but the criteria used to assign F-scale categories do not take into consideration most of these influential factors. For example, one of the criteria for an F-0 rating is that "shallow-rooted trees are toppled". To know if this has occurred, the damage survey team would need to know which trees are shallow-rooted. It would not be unreasonable for team members with some knowledge about trees to assume rooting depth on the basis of the species of each tree, but rooting depth varies among species, with age and developmental stage of trees, and as a function of soil type, depth to water table, and depth to bedrock (Burns & Honkala 1990). Thus a tree of a normally deep-rooted species, if growing over a shallow water table or bedrock, might be much less windfirm that it would be under other conditions (Figure 1).

Figure 1. Trees fallen at the Tionesta '94 site; are these shallow-rooted?

It would be useful to know to what extent simple tree characteristics might be used to estimate treefall risk, and in turn what these risks might imply for F-scale ratings. The objective of this paper is to present my findings on patterns and causes of tree damage, from 9 natural forest sites in eastern North America that were struck by tornadoes. Because tree species and size can be readily determined on site with only modest subjectivity, I will especially explore how these easily-determined characteristics of trees influence wind damage. The null hypothesis that forms the foundation of this effort is that the effects of size and species are consistent among sites and severities. If this null hypothesis is accepted, then size and species are tree characteristics that could be readily incorporated into an improved F-scale assessment protocol. If the null hypothesis is rejected, then the need for further examination of this complex phenomenon becomes clear, and it sounds a cautionary note about applying simple criteria in making F-scale assignments.

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2. METHODS

The findings presented here come from 9 sites where I have examined tree damage caused by tornadoes. All sites are natural forests, although some are old-growth and some are of post-logging origin. They vary substantially in species composition, although several species (e.g. red maple, Acer rubrum) are widespread and abundant in several of the sites. In each case, I surveyed the site within 2-3 years of the tornado event. In the survey, I recorded the following information on a large sample (usually > 300, but less than this at Cathedral Pines and Gould Farm): species, trunk diameter at 1.4 m aboveground [called diameter at breast height or dbh], type of damage, and several other traits that are beyond the scope of this paper. In 7 of the sites, type of damage was categorized, in order of decreasing severity, as: uprooted, trunk broken, crown broken, bent, leaning, branches broken, or intact. Crown broken trees were those that lost > 50% of the pre-storm crown but retained at least one major branch. Bent trees had a bowed trunk, while leaning trees remained straight but were inclined at an angle > 30 degrees from vertical. In two sites (Tionesta '85, and Cathedral Pines) a simpler 3-category assessment was made: uprooted, trunk broken, or standing. In all surveys, trees obviously dead before the storm were excluded from sampling. Some of the findings have been published previously – for the Tionesta '85 site (Peterson and Pickett 1991 & 1995), for the Tionesta '94 site (Peterson 2000), and for the Mingo National Wildlife Refuge site (Peterson and Rebertus 1997).

The primary analytical tool I will utilize is logistic regression (Hosmer and Lemeshow 2000), as implemented in the software package LogExact (version 4, Cytel Software Corp., Cambridge, MA). This technique is superior to standard linear least-squares regression when the reponse variable is binary (takes on one of two possible values, such as "standing" or "fallen"), and estimates the probability of an "event" (e.g. the tree falls) by fitting a logistic curve as a function of the predictor variables. Similarly to linear regression, the slope of the fitted curve, and the odds ratio that can be derived from it, indicate the extent to which risk of the event increases as the predictor variable increases. In the findings presented here, the usual predictor will be tree size as measured by trunk diameter at 1.4 m (dbh, a standard measure that is highly correlated with tree biomass, volume, and height), and the response variable will usually be whether or not a tree has fallen. Thus uprooting and snapping will usually be combined to indicate fallen trees, and all lesser types of damage combined into "standing" trees.

3. RESULTS

While these windthrow events have been described previously in the ecological literature as "catastrophic" (Everham and Brokaw 1996, Webb 1999), it is obvious that they nevertheless reveal a range of levels of forest damage (Figure 2). An immediately-apparent trend is the decrease in relative abundance of the lesser forms of damage from the top to the bottom of Figure 1, which is arranged approximately in order of increasing severity of damage to the forests. As the proportion of all trees toppled increases, the ratio of trees uprooted:trees trunk broken also increases. The ratio of uprooted to trunk broken is significantly correlated with total proportion of trees down (Spearman rank correlation, $r_s = 0.870$, $p < .0001$, n = 9). Thus, more severely-damaged sites have greater abundance of uprooting relative to trunk breakage. Those sites rated F2 had uproot:broken ratios of 2.1, 1.6, 1.9, and 1.7 (mean = 1.82), those rated F3 had ratios of 3.2, 4.4 and 2.3 (mean = 3.3), and the site rated F4 had a ratio of 2.1.

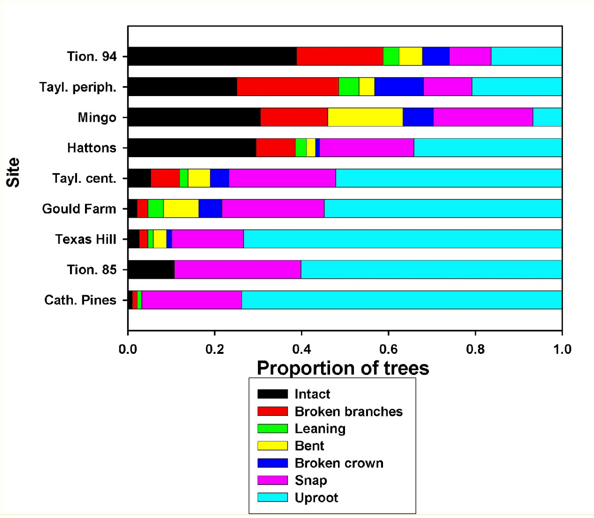

Figure 2. Abundance of types of damage in nince tornado-impacted forests.

Tornado wind damage to forests preferentially damages larger trees; this pattern is consistent across all sites, and is shown by several types of data. First, plotting percent of trees toppled vs percent reduction (before vs after storm) in mean tree size (trunk diameter, dbh), reveals a highly significant correlation r = .799).

Second, in all of the sites, for all species pooled, the logistic regressions of probability of treefall vs tree size (dbh) are positive and significant. However, partially because of smaller sample sizes, this relationship does not always hold for every species considered in isolation at a given site.

The increase in risk of treefall with tree size can be compared among sites by examination of the odds ratios from the logistic regressions. Odds ratios are obtained by exponentiating the slope coefficient of the logit-transform – the beta coefficient. The odds ratios for entire sites range from a low of 1.014 (a 1.4% increase in the odds of treefall for every unit increase in tree dbh at Tionesta '94), to a high of 1.530 (a 53% increase in the odds of treefall per unit size increase at Cathedral Pines), although most of them cluster in the range of 1.05 - 1.20. Thus the role of size in influencing risk of treefall is not consistent among sites, and we must reject the null hypothesis of constant size effects. Nor is there a consistent trend when comparing whole-site odds ratios to the assigned F-scale: the F4 site (Tionesta '85) has an overall odds ratio of 1.094, which is less than that of Cathedral Pines (F3), Hattons (F2, odds ratio = 1.110), and Texas Hill (F3, odds ratio = 1.220).

Beyond the site and size effects, species also strongly influences the probability of a tree suffering wind damage. A simple comparison of species and sites within an intermediate size range is presented in Figure 3, where species that have nine or more trees sampled in the size range of 30 - 50 cm dbh are shown; lines connect species within the same site. Most immediately obvious from the figure is that the proportion of trees fallen is of course much less in the less-damage sites (Tionesta '94, and Taylor Swamp peripheral). More interesting is that this figure does show evidence that typicaly deep-rooted species tend to be more windfirm than their neighbors: sugar maple (Acer saccharum) and especially white oak (Quercus alba) are considered deep-rooted and have strong wood (Burns and Honkala 1990), and clearly suffered less toppling than other species within the same sites. However, white ash (Fraxinus americana) is considered moderately-deep rooted, and shagbark hickory (Carya ovata) is considered deep rooted, yet these two species exhibited no greater windfirmness than their neighbors. It is intriguing to consider whether the damage at the Taylor Swamp peripheral site would have been greater if the two most windfirm species had not been the most abundant at that site. It is also worth noting that in the more severely-damage sites shown in Figure 3, namely Tionesta '85 and Gould Farm, the species other than sugar maple (Acer saccharum) differ little, reinforcing the ecological observation (Everham and Brokaw 1996) that at the highest severities of damage, interspecific differences in vulnerability become obscured because the majority of trees are toppled regardless of species identity.

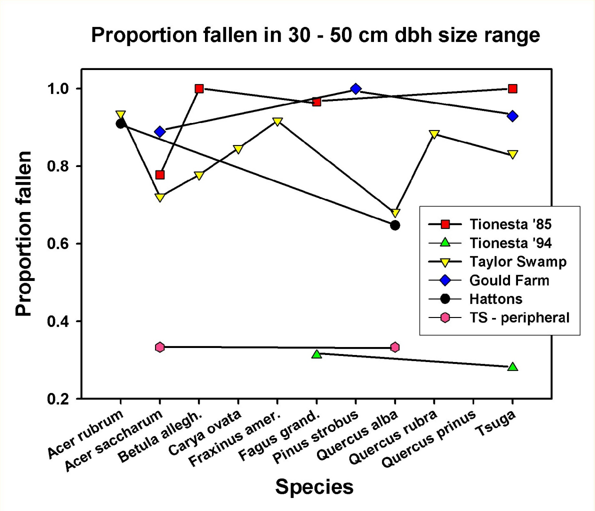

Figure 3. Proportion of intermediate-size trees fallen among sites. Lines connect different species in the same site.

The interaction of size and species is noteworthy, because it demonstrates some of the complexity of treefall patterns. The two most comparable sites, Tionesta '85 and Tionesta '94, are only a few km apart and share similar soils, topography, climate, species compositions and tree sizes. The pivotal difference between the sites is the size and intensity of the 1985 tornado and the 1994 tornado. As a consequence, the relative differences between the two most common tree species, hemlock (Tsuga canadensis) and beech (Fagus grandifolia), shifts with size: in the smallest size classes, hemlock is less vulnerable in the Tionesta '85 site and more vulnerable in the Tionesta '94 site; in both sites, its vulnerability relative to beech reverses in the larger size classes. Similarly, if the Mingo NWR and Hatton's sites are compared for white oak (Quercus alba) and red oak (Quercus rubra), a reversal of their relative vulnerabilities again is seen. Finally, if the Gould Farm site is compared to Tionesta '85 for hemlock and sugar maple, the two species have similar odds ratios at Gould Farm, but at Tionesta, sugar maple has a substantially lower odds ratio than hemlock, indicating a much slower increase in vulnerability with size.

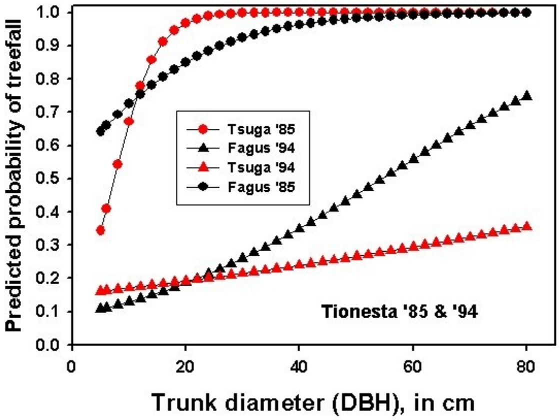

Figure 4. Risk of treefall predicted from logistic regressions for hemlock and beech at two sites, as a function of tree size.

4. DISCUSSION

This brief examination of tree damage patterns at nine eastern U.S. locations struck by tornadoes, has shown some consistent trends. In particular, there is a very general trend of increased tree vulnerability with size, although some individual species may not exhibit this trait at a given site. This trend is widely documented among ecological studies (e.g. Peterson and Pickett 1991, Peterson and Rebertus 1997, Webb 1999, Peterson 2000), although a putative decrease in treefall risk among the largest size classes (Everham and Brokaw 1996) was not observed in any of the studies reported here. Similarly, there is a consistent trend towards greater amounts of uprooting relative trunk breakage, at higher severities of damage. These trends are encouraging and if supported by a broader selection of studies, could be valuable patterns to incorporate in to improved F-scale criteria.

These encouraging trends are also accompanied by several patterns that inspire less confidence. Among-species differences in particular vary among sites and with tree sizes. Although some species considered to be deep-rooted (e.g. white oak and sugar maple) do indeed seem to display greater windfirmness than neighboring trees, other putatively deep rooted species (shagbark hickory and american ash) showed no tendency to be more stable than other species. Even within nearly-identical pairs of sites, the relative vulnerabilities of two common species (hemlock and beech) showed reversals between sites and among size classes. Thus species characteristics, while they undoubtedly influence treefall patterns, do so in a complex fashion that still needs much further investigation. Inclusion of simple among species rankings of windfirmness in F-scale criteria needs refinement and perhaps several types of qualification.

The concluding message these data convey is a mixture of caution and encouragement. Trees may prove to be exceedingly useful for F-scale ratings because they are so common and thus may provide hundreds or thousands of individual “samples” of the wind effects, but the wind-treefall relationship is complex and much remains to be clarified.

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